The activation energy for the FCC rolling texture transition and the activation energy for cross slip

Leffers, T.; Pedersen, O.B.

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

Risø-R-1308(EN)

The Activation Energy for the FCC Rolling Texture Transition and the Activation Energy for Cross Slip

T. Leffers and O.B. Pedersen

Risø National Laboratory, Roskilde, Denmark
January 2002

Abstract Already in 1968 one of the present authors determined the activation energy for the rolling-texture transition in Cu-5%Zn as a spin off of an investigation of the strain-rate dependence of the rolling texture. In the present work this determination of the activation energy is explained and discussed (whereas very few details were given in the original work), and an error in the original work is corrected. The activation energy for the texture transition is compared with recent values for the activation energy for cross slip derived from atomic-scale modelling. After adjustment to a stress level corresponding to the stress in Cu-5%Zn during heavy rolling the theoretical activation energy for cross slip is pretty close to the activation energy for the texture transition. It is concluded that the texture transition is governed by cross slip, and the detailed mechanism is discussed.

ISBN 87-550-2980-9
ISBN 87-550-2981-7 (Internet)
ISSN 0106-2840

Print: Pitney Bowes Management Services Denmark A/S, 2002

Contents

1 Introduction

It is generally accepted that the type of rolling texture developed in fcc metals and alloys (copper-type or brass-type texture) depends on the stacking fault energy, e.g. [1], and the rolling temperature, e.g. [2,3,4]: high stacking fault energy and high rolling temperature favour the copper-type texture. One of the present authors [5] has shown that the type of texture also depends on the strain rate: in brass with 5% zinc, which at room temperature is in the texture transition range, a low strain rate pushes the rolling texture in the direction of the copper type, and a high strain rate pushes the rolling texture in the direction of the brass type (but in both cases the texture is still in the transition range).

This clearly indicates that the type of texture (the texture transition) is governed by a thermally activated process, which is influenced by the stacking fault energy. Cross slip is the obvious candidate for such a process, as first suggested by Smallman and Green [6] and Dillamore and Roberts [7], and it is a widespread belief that the texture transition *is* governed by cross slip - via some mechanism which we cannot claim to know in detail. Leffers [5] actually determined an activation energy for the texture transition (~ 10 kcal/mole) and stated that it was comparable with the theoretical activation energy for cross slip. However, in those days the theoretical estimate of the activation energy for cross slip was not very reliable, and therefore the apparent approximate agreement (within a factor of ~ 2) was considered to be of limited significance. Furthermore, there was an error in the estimated value (see 3.1).

Today the situation is different. We have a reliable theoretical estimate of the activation energy for cross slip [8], and we also have an experimental determination [9] which agrees with (does not disagree with) the theoretical estimate. However, as to be discussed in 5.2, the theoretical and the experimental activation volumes do not agree. The present work provides a revised estimate of the activation energy for the texture transition based on Leffers's data, and the resulting activation energy is compared with the theoretical values for the cross-slip activation energy now available (with due consideration to the stress dependence as described in section 4).

The primary aim of Leffers's work was to demonstrate the strain-rate dependence of the rolling texture. As already mentioned, the estimate of the activation energy for the texture transition was not considered to be very important. As a consequence no details were given. In the present work the determination of the activation energy is the central issue. Therefore, a detailed description of the method used for the determination of the activation energy is presented in section 2, and a detailed description of the relevant parts of the experimental procedure is presented in section 3 - including a detailed description of the relevant parts of the experimental procedure in the work of Alam et al. [10] which is an integral part of the experimental basis for the determination of the activation energy.

2 Determination of the activation energy

Since texture measurements do not directly provide the rate for any specific process, we cannot determine the activation energy by temperature variations alone. We must find combinations of rolling temperature T and strain rate $\dot{\varepsilon}$ which give the same texture. Ideally we should find a number of combinations of T and $\dot{\varepsilon}$ which give the same texture and then find the activation energy from the slope of ln $\dot{\varepsilon}$ versus 1/T. However, such data are not available (and they cannot be provided because of the practical limitation in the variation range of strain rates for rolling, particularly for rolling at controlled temperature).

Instead we combine Leffers's data on the strain-rate dependence of texture in Cu-5% Zn with the data on the temperature dependence of texture in the same alloy by Alam et al. [10]. Fortunately Leffers and Alam et al. use one common parameter for characterization of the texture. Because a large variation in $\dot{\varepsilon}$ is necessary in order to get a significant texture change, Leffers only used two strain rates, the lowest one which could be obtained, $\dot{\varepsilon}_1$, and the highest one which could be obtained, $\dot{\varepsilon}_2$ (both referring to rolling at room temperature). Alam et al. presented a curve showing the texture parameter versus rolling temperature. They did not specify their strain rate, but it would certainly be somewhere between $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ (see section 3).

From the curve of Alam et al. we find the temperature T_1 which gives the same texture parameter as $\dot{\varepsilon}_1$ in Leffers's experiments, and we find the temperature T_2 (lower than T_1) which gives the same texture parameter as $\dot{\varepsilon}_2$. We then know that a specific change in texture (in the direction of the brass type) can be achieved either by a change in strain rate from $\dot{\varepsilon}_1$ to $\dot{\varepsilon}_2$ (at constant temperature, T_{12}, room temperature) or by a change in rolling temperature from T_1 to T_2 (at constant strain rate, $\dot{\varepsilon}_{12}$, not specified).

A specific deformation pattern, and hence a specific texture, is characterized by a specific ratio between the rate of the thermally activated process and the imposed strain rate. Thus we can write the following two equations referring to T_1 and $\dot{\varepsilon}_1$ and to T_2 and $\dot{\varepsilon}_2$, respectively:

$$\nu\cdot\exp(-E/kT_1)/\dot{\varepsilon}_{12} = \nu\cdot\exp(-E/kT_{12})/\dot{\varepsilon}_1 \quad (1)$$

$$\nu\cdot\exp(-E/kT_2)/\dot{\varepsilon}_{12} = \nu\cdot\exp(-E/kT_{12})/\dot{\varepsilon}_2 \quad (2)$$

where ν is a pre-exponential, E is the activation energy and k is Boltzmann's constant. Combining equation (1) and (2) we get the final expression for the activation energy:

$$E = k\cdot\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)/(1/T_2 - 1/T_1) \quad (3)$$

This is the equation to be used for the calculation of E. For the estimate of the possible experimental error in 5.1 we consider the possibility that the strain rates in the experiments of Alam et al. at T_1 and T_2 may be different. We take the strain rate at T_1 (equation (1) to be $\dot{\varepsilon}_{11}$ and the strain rate at T_2 (equation (2)) to be $\dot{\varepsilon}_{22}$. This gives a new equation:

$$E = k \cdot \ln((\dot{\varepsilon}_2 / \dot{\varepsilon}_1)(\dot{\varepsilon}_{11} / \dot{\varepsilon}_{22})) / (1/T_2 - 1/T_1) \quad (4)$$

3 Experimental procedures

3.1 The work of Leffers [5]

A plate of copper with 5 % zinc by weight 10 mm thick and 120 mm wide was cast in argon atmosphere (starting materials copper of 99.98 % purity and zinc of 99.99 % purity). The plate was then rolled to 50 % reduction and cut into two 60 mm wide strips which were recrystallized at 550°C, resulting in an approximately texture-free material. One strip was used for rolling with high strain rate, and one was used for rolling with low strain rate. In both cases the final reduction was 94 %.

Rolling with high strain rate was done with rolls with diameter 343 mm, with rolling speed of 25 m/min. and with a reduction per pass of approximately 50 %, which meant that 94 % reduction was achieved in four passes. Rolling with low strain rate was done with rolls with diameter 83 mm (supported by bigger rolls), with rolling speed 3,5 cm/min. and with a reduction per pass of approximately 10 %, which meant that 94 % reduction was achieved in 30 passes. Leffers used the rolling speed divided by the number of passes to express the relative strain rate, resulting in a strain-rate ratio $\dot{\varepsilon}_2 / \dot{\varepsilon}_1$ of ~ 5000 between rolling with high and low strain rate (exactly 5400). Actually one must correct for the difference in contact length between the rolls and the plate for the large and the small rolls. The real strain rate is inversely proportional to the contact length. The contact length ℓ is calculated from

$$\ell = R \cdot \mathrm{Arc}\cos((R - \Delta t/2)/R) \quad (5)$$

where R is the radius of the roll, Δt is the reduction in thickness per pass, and Arccos is given in radians. For the first pass this means that the above strain-rate ratio should be multiplied by a factor of 0.22, and for the last pass it means that the strain-rate ratio should be multiplied by a factor of 0.16. Thus, the strain rate in Leffers's experiments is not quite constant. We select a correction factor of 0.18 because the texture is predominantly determined at the higher strains. The resulting value of $\dot{\varepsilon}_2 / \dot{\varepsilon}_1$ is ~ 1000. The actual strain rates may be calculated from $\dot{\varepsilon} = \varepsilon p \cdot rs / \ell$, where εp is the strain per pass and rs is the rolling speed. The resulting strain rates are: $\dot{\varepsilon}_1 \sim 0.03\ s^{-1}$ and $\dot{\varepsilon}_2 \sim 30\ s^{-1}$.

Leffers used four different parameters to characterize the texture (to describe the change towards the brass-type texture with increasing strain rate) based on the {111} and the {200} pole figures. One of these texture parameters, TP4, was also used by Alam et al. [10] to describe the change in texture towards the brass type with decreasing rolling temperature, and therefore this is the relevant texture parameter. It was originally proposed by Smallman [11], referred to as $I_{\alpha=0^\circ} / (I_{\alpha=0^\circ} + I_{\alpha=30^\circ})$. It is derived from pole densities in the central part of the {111} pole figure.

Leffers recorded five {111} pole figures for five different samples from the plate rolled with high strain rate and five {111} pole figures for five different samples from the plate rolled with low strain rate with the Schulz reflection

technique [12] using CuKα X-rays. Before the texture measurements the surface layer was removed by a chemical polish (in nitric acid with 20 % water and 2 g $NiCl_3$ per litre).

The results are given in Table 1. For comparison TP4 for the pure copper-type texture (represented by copper) and for the pure brass-type texture (represented by Cu-15 % Zn) are also quoted.

Table 1. The texture parameter TP4.

Material	Individual results					Mean value
Cu						0.85
Cu + 5 % Zn low strain rate	0.81	0.82	0.81	0.83	0.83	0.82 ± 0.01
Cu + 5 % Zn high strain rate	0.73	0.74	0.72	0.74	0.74	0.73 ± 0.01
Cu + 15 % Zn						0.49

3.2 The work of Alam et al. [10]

A plate of copper with 5 % zinc by weight 15 mm thick and 25 mm wide was cast in argon atmosphere (starting materials copper of 99.99 % purity and zinc of 99.995 % purity). The plate was then planed to a thickness of 12 mm. This planed plate was rolled to a thickness of 5 mm and recrystallized at 600°C, resulting in an approximately texture-free material.

The final rolling was performed with a small rolling mill (roll diameter 30 mm) immersed in a bath with temperature controlled within ± 3°C to a total reduction of 95 % in 20 to 50 passes. The rolling speed was not specified so we cannot make a direct comparison with the strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ in Leffers's experiments, but a qualified guess for the rolling speed would be ~ 3 m/min., which means that the strain rate ($\dot{\varepsilon}_{12}$, see section 2) would be approximately 100 $\dot{\varepsilon}_1$. Thus $\dot{\varepsilon}_{12}$ is between $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ as to be discussed further in 3.3.

As Leffers, Alam et al. use various texture parameters to characterize the texture (the transition in the direction of the copper type with increasing rolling temperature). One of them, α_1, is identical to Leffers's TP4. Fig.1 shows the temperature dependence of α_1 for various Cu-Zn alloys. The black triangles refer to the alloy with 5 % Zn. The horizontal and the vertical broken lines in Fig.1 refer to 3.3. Before the texture measurements the surface layer of the specimens had been removed by etching with dilute nitric acid. The texture measurements were made by X-ray diffraction (using CuKα) with equipment which was a further development of the goniometer of Bunk et al. [13].

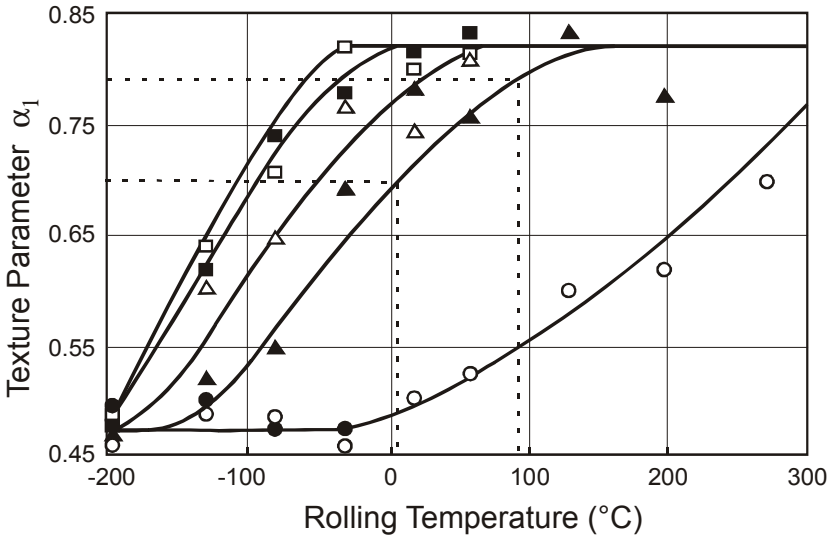

Figure 1. The texture parameter α_1 versus rolling temperature for various Cu-Zn alloys as determined by Alam et al. [10]. The black triangles correspond to Cu-5 % Zn. The broken lines are added by the present authors.

3.3 Calculation of the activation energy

As shown in Table 1 Leffers found TP4 values of 0.85 and 0.49 for the pure copper-type texture and the pure brass-type texture, respectively. Fig.1 shows that Alam et al. found α_1 values of 0.82 and 0.47 for the pure copper-type and the pure brass-type texture, respectively (at high and low temperature). This means that the measuring procedures of Leffers and Alam et al. must have been slightly different. In order to compensate for this difference Leffers's TP4 values of 0.82 and 0.73 for low and high strain rates, respectively, are corrected to 0.79 and 0.70 (by subtraction of 0.03) when they are introduced in Fig.1 as shown by two horizontal broken lines. The vertical broken lines indicate the temperatures corresponding to Leffers's experiments at low and high strain rates: 89°C and 4°C, respectively.

So the suggestion in 3.2 that the strain rates in the experiments of Alam et al. is somewhere between the low and the high strain rate in Leffers's experiments at room temperature is confirmed: the corresponding temperatures are above and below room temperature, respectively.

We now know the relative values of $\dot{\varepsilon}$ and the T values in equation (3): $\dot{\varepsilon}_2 / \dot{\varepsilon}_1$ is ~ 1000, T_2 is 277 K, and T_1 is 362 K. We can then calculate the activation energy: E = 0.70eV.

4 The activation energy for cross slip

Rasmussen et al. [14,15] provided the first atomistically based estimate of the activation energy for cross slip in copper: ~3eV for non-jogged screw dislocations. This activation energy is prohibitively high for cross slip at room temperature – and it is much higher than the activation energy for the texture transi-

tion from 3.3 (0.70eV). Vegge et al. [8] showed that the activation energy for cross slip is drastically reduced by the introduction of jogs – reduced to 0.86eV for cross slip without stress assistance, which is already quite close to the activation energy for the texture transition. And it is obvious that it is relevant to consider jogged screw dislocations at the high strains at which the texture is formed. In this section we attempt to correct the cross-slip activation energy for jogged screw dislocations of Vegge et al. [8] to the value relevant for the situation with high stresses at which the texture transition takes place.

4.1 The stress dependence of the activation energy for cross slip

Already common sense tells us that the activation energy for cross slip depends on stress: an appropriate stress must make cross slip easier. The experiments of Bonneville et al. [9] clearly point to such a stress dependence (there is a finite positive activation volume). Atomistic modelling of the annihilation of screw-dislocation dipoles by cross slip [16, 17] shows that the activation energy decreases with decreasing dipole height.

For the annihilation of screw-dislocation dipoles without jogs in "computer copper" Rasmussen et al. [16] showed that there is an approximately linear relation between the activation energy and the inverse dipole height. For a single non-jogged screw dislocation (inverse dipole height zero) the activation energy is 2.7eV. For a dipole height of four or five {111} interplanar distances, depending on the configuration, the activation energy is zero. For larger dipole heights there is a finite activation energy, i.e. the annihilation is thermally activated. However, unless the dipole height is quite small, the activation energy is prohibitively high for temperatures in the neighbourhood of room temperature, i.e. cross slip of screw dislocations without jogs will not happen at any significant rate at these temperatures as already stated above.

Therefore, we only look at cross slip of screw dislocations with jogs in the present work. Ideally we should repeat the computer modelling of Rasmussen et al. [16] for screw-dislocation dipoles with jogs. However, with the procedure used by Rasmussen et al., the "nudged elastic band", the computer finds an alternative route for the annihilation of screw-dislocation dipoles with jogs [17]: by concerted jog migration the two screw dislocations approach each other until they annihilate by spontaneous cross slip (with zero activation energy) at a dipole height of 11 {111} interplanar distances. The activation energy for this process (for jog migration) is very low, of the order of 10meV. This process may be a realistic bid for the annihilation of jogged screw-dislocation dipoles with low dipole heights, but it cannot be extrapolated to large dipole heights. The required constant supply of jogs of the same type would be unrealistic for the dislocation structures in real materials.

With reference to the work of Rasmussen et al. [16] on the annihilation of non-jogged screw-dislocation dipoles, we assume that there is, for annihilation by a simple cross slip process (without concerted jog migration), an approximately linear relation between the activation energy for the annihilation of jogged screw-dislocation dipoles and the inverse dipole height. We only know two points for this supposedly linear relation: for a dipole height of 11 {111} interplanar distances (2.2 nm) the activation energy is zero, and for a single screw dislocation (inverse dipole height zero) the activation energy is 0.86eV [8,17].

Fig. 2 shows the linear relation based on these two points. We shall now try to replace the abscissa co-ordinates in Fig. 2 (inverse dipole height) by an applied

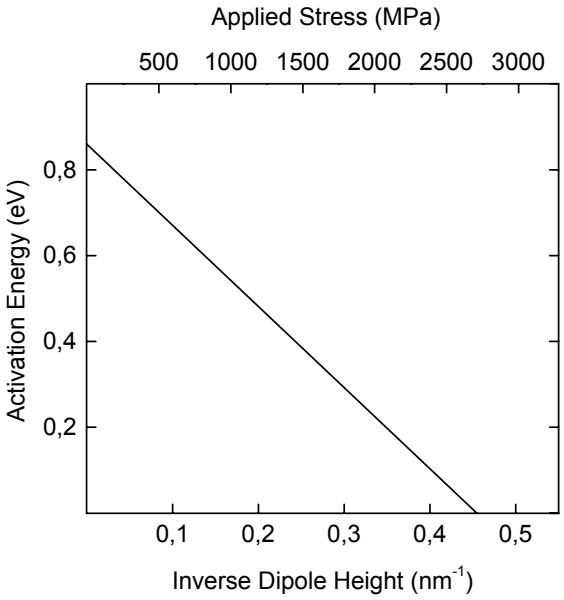

Figure 2. The suggested linear relation between the activation energy for dipole annihilation by cross slip and the inverse dipole height. The alternative abscissa axis indicates an applied stress which assists cross slip (which lowers the activation energy).

stress in order to relate the activation energy to the applied stress. We do not know which stress components lead to the zero activation energy at a dipole height of 11 {111} interplanar distances, and we do not know which stress components are responsible for the approximately linear relation between activation energy and inverse dipole height in the computer experiments of Rasmussen et al. on non-jogged screw-dislocation dipoles. Simplistically we assume that the dependence of the activation energy on the inverse dipole height comes via the shear stress from one of the screw dislocations at the position of the other screw dislocation in the plane common to the two dislocations. Simplistically again this shear stress is:

$$\tau = \mu b / 2\pi r \qquad (6)$$

where μ is the shear modulus for isotropic copper, b is the Burgers vector for an undissociated dislocation, and r is the distance between the two dislocations which is approximately equal to the dipole height. If we convert the inverse dipole height in Fig. 2 to a shear stress via equation (6), we get an activation volume (a slope of the line) of $\sim 10\,b^3$ - not very different from the activation volume of $\sim 15\,b^3$ derived by Rasmussen et al. [16] from the annihilation of non-jogged dipoles.

In connection with texture formation we assume that the effect of cross slip is to help screw dislocations bypass obstacles, and we need to know the effect of an applied stress in this process. Thus, we must convert the shear stress in equation (6), which assists dipole annihilation by cross slip, to an applied stress. First we convert the shear stress to an applied tensile stress by multiplication by the Sachs M factor of 2.22 (the mechanical data available refer to tensile tests). Alternatively we might have multiplied by the Taylor M factor of 3.08, which would have served our purpose even better (see later). For the next step in the conversion we argue that for bypassing obstacles the applied stress on the most

heavily loaded slip system is not the only relevant parameter. The stress on other, less heavily loaded, slip systems such as the cross slip system will also be important (for dipole annihilation we took this stress component to be the decisive stress component). The shear stress in equation (6) should therefore be multiplied by yet another factor larger than unity to relate it to the applied stress. In order to get a simple relation between a certain value of τ in equation (6) and the corresponding applied stress (a factor of 3), we take the above factor to be 1.36. Thus, we convert the abscissa axis in Fig. 2 in terms of $1/r$ to an abscissa axis in terms of an applied stress by multiplication by $3\mu b/2\pi$. This alternative abscissa axis is also shown in Fig. 2. One should notice that if we had selected the Taylor M factor instead of the Sachs M factor, we would have obtained the alternative abscissa axis in Fig. 2 without the additional factor 1.36.

According to Metals Handbook [18] the yield stress of annealed and heavily rolled Cu-5%Zn is ~80MPa and ~400MPa, respectively. Thus, the materials for which the texture has been measured have, during rolling to 94/95% reduction, experienced stresses in the approximate stress range 80-400MPa corresponding to cross-slip activation energies in the range 0.83-0.73eV (Fig. 2). The great majority of the strain takes place at fairly high stresses because of the high initial work-hardening rate, and we must assume that the details of the texture are determined in the strain range with high stresses (rather than in the short strain range with low stresses). Therefore, it is obvious that the cross-slip activation energies to be associated with the texture transition are those close to 0.73eV rather than those close to 0.83eV.

The theoretical activation energy for cross slip refers to “computer copper” with interatomic potentials which reproduce most of the properties of real copper quite well [8,17]. However, the stacking fault energy of computer copper is only 31mJ/m2 which is somewhat lower than that of real copper, but probably quite close to that of Cu-5%Zn, cf. [19].

So we may conclude that the relevant theoretical activation energy for cross slip ($\geq$ 0.73eV and $<<$ 0.83eV) agrees with the experimental activation energy for the texture transition (0.70eV) as discussed further in 5.2.

5 Discussion

5.1 Accuracy of the activation energy for the texture transition

The determination of the activation energy for the texture transition is based on a combination of the experimental results of Leffers [5] and Alam et al. [10]. The reliability of such a combination depends on the similarity between the experimental conditions. As described in 3.1 and 3.2 the starting materials are quite similar. As pointed out in 3.3 the procedures for the measurement of the texture parameters TP4 (Leffers) and α_1 (Alam et al.) must be similar since the results for the pure copper type texture and the pure brass type texture only differ slightly. In the calculation of the activation energy the small difference is corrected for as described in 3.3. Today the trend is to characterize textures in terms of the orientation distribution function (the ODF) rather than in terms of pole figures as done in the present work. However, the characterization of the texture transition in terms of the texture parameters TP4 and α_1 is purely em-

pirical, and a corresponding empirical characterization of the texture transition in terms of ODF data would only lead to extra manipulation of the experimental data. So the fact that we deal with the experimental data in an "old-fashioned way" is only an advantage.

Leffers's results for TP4 in Table 1 are obviously very reproducible. But admittedly they represent data from only one plate rolled with low strain rate and one plate rolled with high strain rate.

The results of Alam et al. in Fig.1 represent different experiments, and there is quite some scatter. However, if we disregard the experiment at 198°C, which also produced odd results for the other texture parameters (see the original work of Alam et al.), the curve for α_1 versus rolling temperature is fairly well defined. The curve most different from the one in Fig.1 which still represent the experimental points reasonably well (not to be shown) gives T_1 and T_2 values of ~330K and ~250K, respectively, which would result in an activation energy of ~0.60eV to be compared with the activation energy of 0.70eV found in 3.3. This gives an idea of the uncertainty introduced by the scatter in the results of Alam et al. (± 0.10eV).

As quoted in 3.2 the reduction to 95 % in the experiments of Alam et al. was achieved in 20 to 50 passes. If we assume that the rolling speed was constant, that implies a possible variation in $\dot{\varepsilon}_{11} / \dot{\varepsilon}_{22}$ by a factor of 2.5 which, according to equation (4), corresponds to an experimental uncertainty of ± 0.05eV. This uncertainty contributes to the scatter in the results of Alam et al., i.e. it is included in the above phenomenological uncertainty of ± 0.10eV.

As described in 3.1 the strain-rate ratio between Leffers's experiments at high strain rate and the experiments at low strain rate varies between 0.22·5400 = 1200 and 0.16·5400 = 900 for the first and the last pass, respectively. We selected a ratio of 1000 on the basis of the assumption that the later stages were most important for the final texture. If we had chosen the highest strain-rate ratio of 1200, that would only increase the activation energy from 0.70eV to 0.72eV, corresponding to an uncertainty of ± 0.02eV which is insignificant compared with the above uncertainty of ± 0.10eV.

Theoretically there is one obvious objection to the present determination of the activation energy for the texture transition: the texture is formed gradually during a very wide range of reductions, from zero to 94/95%, with a large change in stress level which may change the activation energy. However, these are the conditions for the determination of an activation energy for the texture transition: the development of the subtle differences in texture that we must rely on requires high strains. If we accept the conclusion that the thermally activated process governing the texture transition is cross slip (cf. 5.2), this objection is not too serious - because the activation energy for cross slip does not change much in the relevant stress range.

The determination of the activation energy is based on only two points in $\ln\dot{\varepsilon}$-versus-1/T space, i.e. there is no proof of a linear relation. However, with the given experimental conditions we cannot do it better. Even if we constructed a very expensive equipment with well controlled strain rate and rolling temperature, we would still be restricted by a limitation in the variation range of the strain rate. We think it is important to get an estimate of the activation energy for the texture transition even when it is based on non-ideal experiments.

It is obvious that the quoted experimental error of ± 0.10eV only refers to the quantitatively known sources of error. It does not include possible systematic errors.

5.2 Physical significance

In section 4 it is argued that the theoretical activation energy for cross slip in the range of high stresses is ≥ 0.73eV and << 0.83eV, which agrees quite well with the experimentally determined activation energy of 0.70eV ± 0.10eV. Thus, on the basis of our present theoretical knowledge of the cross slip process the present experimental result supports the idea that the fcc texture transition is governed by cross slip - which agrees with the circumstantial evidence presented in section 1.

As to the detailed mechanism for the texture transition, Leffers [20,21] for instance has suggested a composite model for the formation of the brass-type texture, including a "catalytic" effect of deformation twins: initially the deformation twins in the grains with "bundles" enforce slip on one single slip plane (while strain continuity is maintained by multiple slip in the other grains), and subsequently this leads to a stage with predominant shear banding. In terms of cross slip this would imply that cross slip prevents deformation twinning in materials which develop a copper-type texture by reducing the stresses to a level below that required for deformation twinning.

Recently Engler [22] has shown that concentrated Cu-Mn alloys develop a brass-type texture in spite of the fact that they have stacking fault energies similar to that of copper and do not form deformation twins at any significant rate. The explanation for the formation of a texture similar to the brass-type in Cu-Mn alloys may be completely different from that for the "normal" formation of the brass-type texture. However, "planar-slip" (caused by short-range ordering) is one of the explanations suggested by Engler, and such planar slip may be brought about via suppression of cross slip. Thus, the explanation for the formation of a brass-type texture in Cu-Mn may be related to the above explanation for the normal formation of the brass-type texture in terms of slip on one single slip plane as caused by deformation twins which, in turn, form because of a low rate of cross slip.

As mentioned in section 1, Bonneville et al. [9] have made an experimental determination of the activation energy for cross slip in copper (at zero applied stress), resulting in an activation energy of 1.15eV ± 0.37eV. This apparently agrees with the theoretical activation energy of 0.86eV for cross slip of jogged screw dislocations in computer copper (at zero applied stress) determined by Vegge et al. [8]. However, the experimental activation volume (defined as $dE/d\sigma$ where E is the activation energy and σ is the stress) determined by Bonneville et al., 250 b^3 or even bigger, and the theoretical activation volume quoted in 4.1, 10 b^3 (and the theoretical activation volume of 15 b^3 determined by Rasmussen et al. [16]), are very different. Rao et al. [23] quote a theoretical value of 20 b^3 for the activation volume in copper (derived from atomistic calculations for nickel). There are thus three more or less independent theoretical indications of low activation volumes of the order of 10-20 b^3 as used in 5.1 to justify the present experimental procedure for the determination of the activation energy for the texture transition and to justify the conclusion that the texture transition is governed by cross slip. We shall not here go into a detailed discussion of the disagreement between the theoretical and the experimental activation volumes. For a discussion of this disagreement we can refer to Püschl [24].

6 Conclusion

The activation energy for the fcc rolling-texture transition in Cu-5 % Zn has been determined by combining the observations of the strain-rate dependence of the texture by Leffers [5] and the observations of the temperature dependence of the texture by Alam et al. [10]. The resulting activation energy is 0.70eV ± 0.10eV, which agrees with the theoretical estimate of the activation energy for cross slip, ≥ 0.73eV and << 0.83eV, based on atomistic modelling [8,16,17]. The most serious possible objection to the procedure for the determination of the activation energy for the texture transition is that the textures considered form over a very wide range of strains and hence over a very wide range of stresses. However, if we accept the conclusion that the texture transition is governed by cross slip, and if we accept the theoretically determined activation volume for cross slip, this objection is not very serious.

Acknowledgements

The authors want to acknowledge helpful discussions with K.W. Jacobsen and T. Vegge and the access to the unpublished work of W. Püschl. The work was carried out within the Engineering Science Centre for Structural Characterization and Modelling of Materials.

References

1. Haessner, F., *Z. Metallkde.,* 1962, **63**, 403.

2. Hu, H., Cline, R.S. and Goodman, S.R., *J. Appl. Phys.,* 1961, **32**, 1392.

3. Hu, H. and Cline, R.S., *J. Appl. Phys.,* 1961, **32**, 760.

4. Hu, H. and Goodman, S.R., *Trans. Met. Soc. AIME.*, 1963, **227**, 627.

5. Leffers, T., *Scripta metall.,* 1968, **2**, 447.

6. Smallman, R.E. and Green, D., *Acta metall.*, 1964, **12**, 145.

7. Dillamore, I.L. and Roberts, W.T., *Acta metall.,* 1964, **12**, 281.

8. Vegge, T., Rasmussen, T., Leffers, T., Pedersen, O.B. and Jacobsen, K.W., *Phil. Mag. Lett.,* 2001, **81**, 137.

9. Bonneville, J., Escaig, B. and Martin, J.L., *Acta metall.,* 1988, **36**, 1989.

10. Alam. R., Mengelberg, H.-D. and Lücke, K., *Z. Metallkde.*, 1967, **58**, 867.

11. Smallman, R.E., *J. Inst. Metals,* 1955/56, **84**, 10.

12. Schulz, L.G., *J. Appl. Phys.,* 1949, **20**, 1030.

13. Bunk, W., Lücke, K. and Masing, G., *Z. Metallkde.*, 1954, **45**, 269.

14. Rasmussen, T., Jacobsen, K.W., Leffers, T. and Pedersen, O.B., *Phys. Rev. B*, 1997, **56**, 2977.

15. Rasmussen, T., Jacobsen, K.W., Leffers, T., Pedersen, O.B., Srinivasan, S.G. and Jónsson, H., *Phys. Rev. Lett.*, 1997, **79**, 3676.

16. Rasmussen, T., Vegge, T., Leffers, T., Pedersen, O.B. and Jacobsen, K.W., *Phil. Mag. A,* 2000, **80**, 1273.

17. Vegge, T., Pedersen, O.B., Leffers, T. and Jacobsen, K.W., in *Mat. Res. Soc. Symp. Proc. Vol. 578*, Materials Research Society, 2000, p. 217.

18. *Metals Handbook*, Ninth Edition, Vol. 2, American Society for Metals, Metals Park, 1979, p. 316.

19. Gallagher, P.C.J., *Metall. Trans.*, 1970, **1**, 2429.

20. Leffers, T., in *Textures of Materials, ICOTOM-11*, eds. Z. Liang, L. Zuo and Y. Chu, International Academic Publishers, Beijing, 1996, p. 299.

21. Leffers, T., in *Thermomechanical Processing of Steel*, eds. S. Yue and E. Essadiqi, Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, 2000, p. 65.

22. Engler, O., *Acta mater.*, 2000, **48**, 4827.

23. Rao, S., Parthasarathy, T.A. and Woodward, C., *Phil. Mag. A*, 1999, **79**, 1167.

24. Püschl, W., *Progr. Mater. Sci.* (in press).

Bibliographic Data Sheet **Risø-R-1308(EN)**

Title and authors

The Activation Energy for the FCC Rolling Texture Transition and the Activation Energy for Cross Slip

T. Leffers and O.B. Pedersen

ISBN	ISSN
87-550-2980-9 87-550-2981-7 (Internet)	0106-2840

Department or group	Date
Materials Research Department	8 January 2002

Groups own reg. number(s)	Project/contract No(s)

Sponsorship

Pages	Tables	Illustrations	References
17	1	2	24

Abstract (max. 2000 characters)

Already in 1968 one of the present authors determined the activation energy for the rolling-texture transition in Cu-5%Zn as a spin off of an investigation of the strain-rate dependence of the rolling texture. In the present work this determination of the activation energy is explained and discussed (whereas very few details were given in the original work), and an error in the original work is corrected. The activation energy for the texture transition is compared with recent values for the activation energy for cross slip derived from atomic-scale modelling. After adjustment to a stress level corresponding to the stress in Cu-5%Zn during heavy rolling the theoretical activation energy for cross slip is pretty close to the activation energy for the texture transition. It is concluded that the texture transition is governed by cross slip, and the detailed mechanism is discussed

Descriptors INIS/EDB

Available on request from Information Service Department, Risø National Laboratory,
(Afdelingen for Informationsservice, Forskningscenter Risø), P.O.Box 49, DK-4000 Roskilde, Denmark.
Telephone +45 4677 4004, Telefax +45 4677 4013